Computed Tomography (CT) Standards

Federal Manufacturing & Technologies

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KCP-613-6277

Published February 2000

Topical Report

NDE Program R&D Support, LA-ESP96-19

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Prepared Under Contract Number DE-ACO4-76-DP00613 for the
United States Department of Energy

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64141-6159

A prime contractor with the United States

Department of Energy under Contract Number

DE-ACO4-76-DP00613.

Honeywell

KCP-613-6277

Distribution Category UC-706

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1 Material Comparisons

Abstract

There is currently no standardized method to check the measurement capabilities of computed tomography (CT) systems within industry. The current method to determine the functionality of CT systems is by use of a test phantom to represent the actual part to be tested. A standard method to check the software algorithms when measuring such parameters as density of a material and the size of an object is not readily available. Many different materials are evaluated by CT systems. A set of standards necessitates the inclusion of materials that cover the gambit of materials encountered. The Federal Manufacturing & Technologies (FM&T) CT standards are designed to accommodate a variety of materials and several different sizes. This provides a method to check the CT system for size measurement capabilities and material density measurement as well as aid in optimizing the geometric parameters of the machine configuration.

Summary

Initial research indicated that the National Aeronautics and Space Administration (NASA) had built a set of computed tomography (CT) standards for their large systems, but there were no small standards available for industrial CT systems of the sizes used in the Weapons Complex. The set developed by NASA required that square holes be cut with 0.0035 mm maximum corner radii and be 0.5 mm square. This requires special machining capabilities. Enhanced Surveillance Projects (ESP) use CT to determine the condition of weapons in the stockpile. It became apparent that a set of standards was necessary to ensure that the CT systems in the normal industrial sizes (4- to 6-inch diameter turntables) were consistent and accurate in their operations from day to day. Based on the NASA standards, but to a much smaller scale and with machinability designed in, CT standards were designed and tested in Honeywell Federal Manufacturing & Technologies (FM&T's) efforts for the R&D Support ESP project.

The CT standards design includes three sizes of ring holders that can be separated and used independently. Inserts of various materials can be put in the ring holders that, in turn, have holes for insertion of wire rods of differing materials. The holders also have drilled cups for holding liquids such as water, oil, etc. having homogenous density properties. The holders are made of Lucite™, stainless steel, and aluminum. A complete set of each was built. The rings are interchangeable among the sets. The three rings are 50 mm, 100 mm and 150 mm in diameter. The height of the rings is 10 mm. The materials used for the wire rods for insertion into the inserts are copper, aluminum, and stainless steel.

Two sets of the standards were fabricated. One is at Los Alamos National Laboratory and the other is in use at FM&T. At FM&T tests were run on the 420-kV X-ray CT system with excellent results. FM&T has a Cobalt 60 CT system, and the standards will be applied to that system when it becomes available.

The CT standards were designed for individual slice CT analyses. Modification may be necessary for area CT scanning, which is planned for investigation at FM&T in FY 2000.

Discussion

Scope and Purpose

An Enhanced Surveillance Project (ESP) program was initiated in 1996 for R&D support of a project being sponsored by Los Alamos National Laboratory (LANL). Computed tomography (CT) is a basic tool used in the enhanced surveillance of the stockpile of weapons. In order to use a CT system as a diagnostic tool for stockpile surveillance, there is a need for a set of CT standards to monitor the performance of the CT systems. Federal Manufacturing & Technologies (FM&T) undertook, with LANL approval and support, the design of CT standards useful with CT systems throughout the weapons complex, but primarily at FM&T and LANL. Two sets of standards were built to allow parallel studies to be conducted by FM&T and LANL so that different types of CT systems could be studied. The standards are not product or program limited.

Prior Work

The National Aeronautics and Space Administration (NASA) had the need to calibrate their CT system. They were looking at large CT systems to accommodate parts up to 5 feet in diameter. The system consisted of mother rings with the center ring essentially a disc and the others annular, concentric rings of ~2 inches wide each and 10 mm thickness. The diameter of the largest ring was 14 inches. They had inserts of 25 mm square and 25 mm diameter. The FM&T standards are based on the NASA design and are scaled down to fit CT machines available at LANL and other weapons complex machines capable of handling weapon parts.

Activity

The procedure for developing the CT standards was to first establish a satisfactory design. The next step was to create the definition, including drawings of the standards. The third step was to fabricate the standards. Finally, testing of the standards was required on CT systems to prove-in the standards and familiarize engineering and operators with the standards system and determine any difficulties in use of the standards.

Development

Internet searches and literature searches were used to gather information concerning types of designs and their applicability to industrial applications. The vast majority of the designs were for medical applications. Internet searches led to a patent from the National Aeronautics and Space Administration (NASA) that had developed a calibration set of standards for its CT system, which was capable of handling parts up to 5 feet in diameter. CT systems at FM&T and

LANL were designed to work with much smaller parts (4-6 inches in diameter). Contact was made with NASA's CT calibration expert to determine the status of the patent and to determine any problems that might have been encountered in the manufacture or use of the set of standards. The design of the FM&T CT standards are generally patterned after the NASA CT calibration standards (reference 1 – abandoned patent number 5,056,130 assigned to NASA). Several improvements were made to the NASA design.

The FM&T standards are much smaller and easier to manufacture than the NASA units and designed to accommodate the materials and machines used in the weapons complex with emphasis on what is expected to be encountered at FM&T and LANL.

Definition

The drawings of the CT standards were computer generated using Pro-E software (reference 2). Several changes were made to the original NASA design. These changes were made to adapt the standards to the CT systems in use in the complex, make them easier to manufacture, provide a better accommodation to the use of liquids, and select materials representative of those encountered in the testing applications in the weapons complex. An exploded view of the standards is shown in Figure 1. (All figures appear following the text.)

The outside dimensions of the annular rings were established at 150 mm and 100 mm with a center disk of 50 mm in diameter. The design will allow the use of standards on tables as small as 2 inches in diameter.

To aid in manufacturing, the use of small square holes in the inserts was eliminated in favor of round holes. This change provided for the use of standard wire sizes to be used as the wire rods. The use of standard wire sizes prevented the need to machine rods as small as 0.5 mm diameter when wire of this diameter can be purchased.

To better accommodate the use of liquids, pockets were placed in the two outside rings. This allows the rings to be taken off of the machine to dump the liquids following testing. It also allows the use of liquids in addition to all of the necessary combinations of other materials in the same test setup.

Materials selected for use in this project were stainless steel (wire, inserts, and rings), aluminum (wire, inserts, and rings), copper (wire and inserts) and Lexan (inserts and rings). The use and configurations chosen were done so as to provide the types of materials that would be encountered in use and allow the embedding of materials in the types of configurations that might be encountered. For example, an aluminum casing with lower density potting material, having an iron core coil with copper wires, would be represented by one of the annular aluminum rings with a Lexan center disk and a steel insert with copper wires inserted into it. Figure 1 provides an exploded view of how the assembled components would be arranged.

Fabrication

The first set of standards was fabricated in the FM&T model shop. The second set was contracted to a local machine shop. Some changes were made to the design during this phase to accommodate machining. The hole diameters in the inserts were changed to accommodate the availability of wire that could be purchased at the time. The changes were made with due consideration as to how the changes would affect results. The changes in diameters were such that the only effect on the final outcome would be in the tenths of millimeter range as far as measurement of sizes. This was deemed insignificant, since the purpose was to start with a known diameter and verify that the software does in fact have the capability and repeatability to measure a known distance. The wire sizes used are 24 AWG (0.51-mm diameter) copper and aluminum, 18 AWG (1.02-mm diameter) copper and aluminum, 12 AWG (2.052-mm diameter) copper and aluminum, 26 W&M (0.459-mm diameter) steel, 19 W&M (1.041-mm diameter) steel, and 14 W&M (2.032-mm diameter) steel. These standard wire sizes correspond to approximately 0.5-mm, 1-mm, and 2-mm diameters for all three materials. Standard twist drill sizes used to drill the holes in the inserts are 0.5 mm, #58 (1.067 mm), and #45 (2.083 mm) to accommodate all of

the wires. All changes were incorporated into the drawings during the build of the first set of standards, and the second set was built to the same final drawings as the first set.

Testing

The standards were imaged using the 420kV X-ray CT system at FM&T, LANL CT system, and Pantex X-ray CT machines. The first set of standards that was made was provided to LANL to perform experiments at their facility and to make comparison studies with Pantex. These studies will be used to determine whether algorithms used on different systems will provide consistent results when scanning the same test items. These studies are being conducted by LANL. The data from the scans at FM&T will be provided to support these studies. The FM&T set of standards will also be employed to verify measurement software on the two systems in house. The test plan used for the experiments with the standards is shown in Figure 2.

The testing was conducted on the X-ray based CT system using four experiments. The first experiment was to investigate the steel standards in various configurations. The second was to evaluate the aluminum standards. The third was to evaluate the Lexan standards. The final experiment was to evaluate the standards as a combination of materials. This would provide an indication of how well the system could resolve different densities in close proximity. The 420KV X-ray system has enough penetrating power for approximately 3 inches of steel. This means that the system should only be able to provide adequate detail in a CT slice on the 50-mm center steel insert. This is the case as is shown in Figures 3 through 7. This is because nearly 100% of the X-rays are either absorbed or scattered by the material. The materials used in this experiment, ranked from most difficult to penetrate to least difficult to penetrate, are listed in Table 1. To gain detail from the steel components in the set of standards, the total thickness of steel material must be less than three inches. The rest of the materials are well within the limits

for the 420-kV system. This limitation for penetration will also apply to any test items that will be processed on the system. As can be seen from Table 1, copper with a thickness greater than 2.5 inches would also present a problem for the 420-kV system. Since there are no rings made of copper, and the total thickness of copper that can be aligned with the X-ray beam when using the standards is less than one inch, this material does not become a problem in the application of the standards.

Table 1. Material Comparisons

Material	Approximate Penetration Thickness in Inches	
	420 kV	Cobalt 60
Copper	2.5	5.7
Steel	3	6.2
Aluminum	9	19
Water	22	42.5
Plastic	23	49

The FM&T Cobalt 60 based CT system was not available for use on the set of standards, but as can be seen from Table 1, the penetrating power of this system would not prohibit the use of the Cobalt system on the standards. The resolution on the Cobalt 60 system is not as good as the X-ray-based system and this will affect the ability to see as much detail. The standards will be scanned with the Cobalt system once it is repaired and available.

A phenomenon that occurs with radiography of materials is filtering of the X-ray beam. Essentially, the X-ray beam from an X-ray tube contains a spectrum of energies with the peak in the spectrum appearing at the energy level being controlled as the kV setting for the control system. In these experiments, the peak in the X-ray spectrum occurs at approximately the 420-kV energy level. As the X-ray beam passes through a material, the beam is "filtered." This means that the detectors will not see the full spectrum of radiation being produced. This also means that other materials may filter out the wavelengths that would be associated with a material of interest, making it very difficult to image that material.

With the limitations of scatter, absorption, and filtering in mind, the results of the scans can be evaluated slice by slice. The slice shown in Figure 3 consists of a steel outer ring, steel center ring, and steel inner ring with steel inserts. No wires were used in the inserts and the two pockets were filled with water. Very little detail can be seen in this particular slice. This is mainly due to the absorption and scattering of the X-ray beam by the steel material making detail difficult to image.

The slice in Figure 4 has the inner and center rings of steel with steel inserts. No wires were used in the inserts. The pocket on the center ring is filled with water. This slice has more detail beginning to show up in the scan, but the thickness of material is still such that there is significant absorption of the X-ray beam.

Figure 5 provides very good detail and is made up of only the inner ring. There were no wires in the insert for this slice. The thickness of the material is such that the entire thickness can be penetrated so that there are enough X-rays passing through the material to the detectors to produce a good image.

Figure 6 is a slice of only the center ring of steel with steel inserts and water in the pocket of the ring. No wires were present. The total thickness of the material is approximately 50 mm. The detail in this slice is better than Figure 4 since there is less material to pass through. The detail is not as good as in Figure 5, even though the material thickness is nearly the same. The difference is the amount of scatter caused by the geometry of the part. The air space in the center should be as dark as the small holes in the inserts, but the scattering of X-rays from the material in the large space is greater due to the larger curvatures involved.

Figure 7 has poorer detail than Figure 6, again mainly due to the scattering effects of the material even though the mean material path is nearly identical. The evaluation of the steel material shots clearly indicates that not only are the material densities of concern in the item being scanned, but the geometric configuration is important as far as scatter is concerned.

The slice in Figure 8 contains all aluminum rings and inserts with no wires and water in the pockets of the center and outer rings. Aluminum is much easier to penetrate and this is evident in the amount of detail observable through the entire 150 mm of material. The difference in density between air, water, and aluminum is very discernable. There is some amount of scatter evident, but much less than with the steel material.

Figure 9 is a slice with all Lexan rings and inserts with water in the pockets of the two outer rings. There is less contrast between the plastic material and water, due to the two materials being close to the same radiographic density and allowing for the fact that Lexan does scatter X-rays more than aluminum due to its internal structure.

Figure 10 is a combination of materials and was used to look at the ability to contrast various materials intermingled in a test configuration. Figure 10 has been adjusted to see the most detail and contrast so that the copper wires in the steel insert can be seen. When this is done the plastic rings and inserts appear to be absent. To make the plastic rings and inserts visible, the ability to see the higher densities would be impaired. The combinations of materials used shows the ability to discern between different materials in close proximity. The combination of a steel insert in an aluminum ring with copper wires indicates the ability of the system to contrast three different densities with the highest radiographic density being the copper wires, followed by the steel insert and then the aluminum ring. Many configurations can be used with this set of standards, and the makeup of typical test item materials should be used as the guide for picking the combination to be used. The CT system has the ability to adjust the way in which an image is viewed.

The material configuration used for each of the scans performed is shown in Figure 2. The assembly of the standards is shown as an exploded view in Figure 1.

Accomplishments

In 1996 LANL presented an ESP plan for R&D work for developing devices to aid in the surveillance of weapons in the stockpile. FM&T determined the need for a set of standards for Weapons Complex CT systems. The use of nondestructive CT is a test method that can be applied to weapons in the stockpile at various stages.

A search of the Internet revealed that NASA (reference 1) had designed a set of standards for their CT systems, but their standards were not directly applicable to those needed in the weapons complex. The NASA design served as a guide for FM&T standards.

The FM&T CT systems consist of a 420-kV X-ray-based CT unit and a Cobalt 60 based unit. The X-ray unit has a six-inch diameter turntable, while the Cobalt CT system has a four-inch diameter table. FM&T standards were designed to apply to both CT units. The standards consist of three concentric rings: one set made of stainless steel, one of Lexan, and the other of aluminum. The two outer rings accommodate both square inserts and round inserts and the center ring can accommodate a single square insert. Each insert has holes for insertion of wire samples. The wire materials that were used are copper, aluminum, and steel of three diameters for each material.

Two sets of standards were built. One is at LANL for their use; the other is in service at FM&T. The LANL set was taken to Pantex for testing on their Linac machine. Results were impressive. The Linac was able to penetrate the three steel rings and determine less dense components within the standards. LANL is using the standards for their flat panel, digital radiography studies with good results.

To prove-in the standards, a test plan was devised and applied to the X-ray CT system. The first experiment was to investigate the steel standards in various configurations. Water was placed in the two cups drilled into the two outer rings, one in each ring. The setup for testing of the steel standards and

their test results are as follows:

- The first test configuration was of the steel standard set complete with all steel components except no wire pins were installed. Results are shown in Figure 3. Note that the 420-kV CT system is not well suited for slicing six inches of steel. Hardly any details of the standard set are visible.
- In the next configuration the outer ring was removed. Results are displayed in Figure 4 and show an increase in detail of the features. The cup with water in the second ring is visible, and the two sets of larger holes in both inserts of the second ring have become visible.
- The third configuration was with the two outer rings removed. The results, Figure 5, are excellent. The center ring is two inches in diameter with a single square insert with holes for three different sizes of wire pins. All details are vividly apparent.
- The fourth configuration was of the second ring only (inner and outer rings missing) with water in the cup but no pins in the inserts. All features are visible as seen in Figure 6, even though there is evidence of scatter.
- The fifth configuration was of the outer ring only with water in the cup and no pins in the inserts. The features are visible as seen in Figure 7, but there are some false indications in the center of the ring due to scatter of X-rays through the material.

The second experiment was for the aluminum standard set. All rings were used and water placed in the two cups. No pins were used in the inserts. The results of this slice are displayed in Figure 8. All features are visible, showing that the CT system can penetrate the six inches of aluminum satisfactorily.

The third experiment was of the Lexan material set of standards. All rings are in place, along with Lexan inserts, water in the cups, and no pins in the inserts. The test results are shown in Figure 9. All features are readily visible in the figure. Lexan is by far the easiest material of those used for rings and inserts to penetrate with the CT system.

The fourth experiment was of a combination of materials of the standards sets. The outer ring, the insert in the inner ring, and all pins in the square insert of the outer ring were of aluminum. The inner two rings and the two inserts in the second ring are Lexan. The two inserts in the outer ring are steel. There is no water in the cups. The round insert in the second ring, the insert in the inner ring, and the square insert in the outer ring have copper pins in all of their holes. The test results in Figure 10 show that the details when used in combination can be imaged.

Future Work

The CT standards will be measured in Metrology for all features and the record will be readily available whenever needed.

The standards will be applied to the Cobalt 60 CT machine when the machine is repaired and back in service and a need for the machine arises. The intent is to use the standards on both the X-ray CT and the Cobalt 60 CT machine.

Plans include the use of the standards in real time radiography studies to determine standardization of the system responses. They will be useful to characterize the lens-coupled capability that is planned for the real time system in FY 2000. The lens-coupled system has been designed and will be installed during that time frame. Also, CT capability with area scan is planned for the real time system.

References

- H. P. Engel, "Computerized Tomography Calibrator," National Aeronautics & Space Administration, United States Patent Number 5,056,130, October 1991.
- D. Hayden, "Los Alamos National Laboratory Enhanced Surveillance Program (ESP) Task Summaries, NDE Program R&D Support," LA-ESP96-19 (FM&T Number 708024), June 1996.

Figure 1. Exploded View of Standards

Experiment #1

Items A,B,C,D,E,F,G,H – Steel stel_1a1.tif as described

Items J,K-Water stel_1b1.tif = ring A missing

Items D1-D9, E1-E9, F1-F9, stel_1c1.tif = ring A&B missing

G1-G9, H1-H9 – Air stel_1m1.tif = ring A&C missing

stel_1o1.tif = ring B&C missing

Experiment #2

Items A,B,C,D,E,F,G,H – Aluminum alum_1a1.tif as described

Items J,K – Water

Items D1-D9, E1-E9, F1-F9,

G1-G9, H1-H9 – Air

Experiment #3

Items A,B,C,D,E,F,G,H – Plastic plas_1a1.gif as described

Items J,K – Water

Items D1-D9, E1-E9, F1-F9,

G1-G9, H1-H9 – Air

Experiment #4

Items A, F, D1-D9 – Aluminum comb_1a1.tif as described

Items B,C,E,G – Plastic

Items D,H, G1-G9 – Steel

Items J, K – Air

Items E1-E9, F1-F9, H1-H9 – Copper

Test Plan

Figure 2. Test Plan and Format for Figures

Figure 3. Steel: Water, No Pins

Figure 4. Steel: Outer Ring Missing, Water, No Pins

Figure 5. Steel: 2 Outer Rings Missing, No Pins

Figure 6. Steel: Inner and Outer Rings Missing, Water and No Pins

Figure 7. Steel: 2 Inner Rings Missing, Water and No Pins

Figure 8. Aluminum: Water and No Pins

Figure 9. Lexan Rings: Water and No Pins

Figure 10. Combination: Outer Ring and Center Insert--Aluminum; Center and Inner Rings and Both Inserts in Center Ring--Lexan; Inserts in Outer Ring and Pins in Square Insert in Center Ring--Steel; No Water; Pins in Round Insert in Center Ring, Center Insert and Square Insert in Outer Ring--Copper